- PART 1 -

Drafting the PRC

Poplar Rule Curves (PRC) - IFN for Riparian Poplars in the South Saskatchewan River Basin

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1. Introduction:

Riparian[1] poplars (cottonwoods) are an important part of riparian ecosystems in the South Saskatchewan River Basin. Particularly in the semi-arid prairie regions of southern Alberta, cottonwoods are often the only native tree species present. Cottonwood groves that occur on river floodplains provide habitat and food sources for many wildlife species. Cottonwoods stabilize floodplain sediments and thereby influence channel movements. They also contribute organic debris and shade to help maintain the aquatic ecosystem.

Cottonwoods are well adapted to their riparian existence in this dry region known for its extremes in temperature. Despite being sensitive to drought stress, riparian cottonwoods are able to survive because they are phreatophytic[2]; they are linked directly to a dependable water supply from the riparian water table through a deep root system. Cottonwood reproduction is also adapted to riparian conditions. Each mature female tree can release millions of seeds each year. The timing of seed release coincides with the springtime peak in river flows. Seed germination occurs rapidly on moistened sediments that have been cleared of vegetation by spring flooding. Seedling root growth is rapid to maintain contact with the moist capillary fringe[3] above the receding water table. Although they are vulnerable to flow-related scouring and burial in their first several years, saplings become increasingly resilient as they grow to maturity. After their roots are established, saplings are capable of re-sprouting vigorously when buried or decapitated.

Cottonwoods are adapted to natural river flow patterns. Thus, changes to minimum, moderate and peak flows can impact these trees in many ways. Reduced minimum flows can result in a corresponding lowering of the riparian water table. If the water table is dropped below the depth that cottonwood root systems can access, the trees will become drought stressed. This stress can lead to branch die-back or tree death depending on the severity and duration of the drought condition. Reductions to moderate flows can also impact cottonwoods because moderate flows recharge the floodplain water table and

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[1] The word 'riparian' relates to the floodplain and adjacent banks of watercourses such as rivers and streams.

[2] Phreatophytes are plants with a tap root system extending to the water table; they can transpire at a high rate even in the desert, so long as the water table does not drop below the tap root (Fetter 1994).

[3] The capillary fringe is a zone of moisture that extends above the saturated riparian water table due to the 'wicking' effect caused by the surface tension of water (Mahoney & Rood 1998). The height of the capillary fringe is dependent upon substrate texture, ranging from 20 to 40 cm for coarse-textured mixtures of cobble and gravels, and 30 to 100 cm for fine-textured silt and sands (reviewed by Mahoney & Rood 1998).

enhance overall forest health by providing higher zones of moisture for young saplings and trees on higher floodplain terraces. In addition to minimum and moderate flows, higher flows are also essential to cottonwoods because the magnitude, duration, and seasonal timing of peak flows are basic to the recruitment and long-term survival of seedlings. Thus, changes to peak flows can cause inadequate seedling recruitment and lead to the gradual deterioration of riparian forests.

This project involved researching instream flow needs (IFN) for riparian cottonwoods in the South Saskatchewan River Basin (SSRB). The final objective was a set of operational flow targets based on naturalized historic flows. Similar to the widely accepted fishery equivalents, termed 'Fish Rule Curves', this project's 'Poplar Rule Curves' (PRC) are designed to provide practical flow-management guidelines for meeting the minimum, moderate and high flow requirements of cottonwoods to help preserve and restore downstream riparian forest ecosystems.

2. Links Between Cottonwood Biology & Hydrology:

Riparian cottonwoods are intimately dependent upon the riparian water table. Despite growing in the driest regions of southern Alberta, cottonwoods are extremely sensitive to drought stress (Tyree et al. 1994). They are able to survive in such dry environments only because their phreatophytic root systems tap into the riparian water table[4], connecting them to a reliable water supply even during natural seasonal changes in temperature and precipitation. Although the limit of cottonwood root growth is not fully known, it may be deduced that the roots of established cottonwoods growing on raised floodplain terraces may penetrate to depths greater than 5 meters to reach the saturated zone.

Although poplars can grow vigorously, they are relatively short-lived trees (their lifespan is usually less than 100 years), and riparian areas are prone to disturbances that can continually reset forest succession. For these reasons, riparian poplar forests require ongoing reproduction to drive forest colonization and replenishment. Every year, each mature female cottonwood can release millions of seeds during a 2-3 week period in early June. Each cottonwood seed is only about 1mm long and has a cottony enclosure of fine hairs that aids dispersal by wind and water. Since each tiny seed contains a very small energy reserve, seed viability is limited to a few weeks. Germination will occur on any moist substrate, but for a cottonwood seedling to successfully grow into a mature phreatophytic tree, it requires specific substrate and moisture conditions during its first few weeks and subsequent growing season.

Recently deposited sediments, or those scoured by ice or flood flows, provide the moist, barren seedbeds that are suitable for cottonwood seedling establishment. Once moistened, a cottonwood seed will germinate within 24 hours and immediately begin root elongation at a rate of about 0.5 to 1 cm / day, reaching a length of about 60 cm after the first growing season (Mahoney & Rood 1998). As springtime streamflows recede, so does the riparian water table. Young cottonwood seedlings will only survive if their root growth is able to keep pace with the moist capillary fringe above the declining water table. If the substrate dries out too quickly, the young cottonwoods will be vulnerable to desiccation. If the site is repeatedly flooded, seedlings can be buried by sediments or scoured away.

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[4] The riparian water table consists of streamflow that has infiltrated the streambed. This zone of saturation extends horizontally from the stream's surface and slopes gradually downward.

The precarious establishment of cottonwood seedlings is limited to a narrow elevational band above the river level. This 'recruitment zone' is defined at the top by a combination of root growth potential plus the extent of capillary fringe above the water table during late summer streamflows, and at the bottom by the potential for subsequent scouring and deposition (Figure 1). Consequently, the recruitment zone extends from about 60 cm to about 150 to 200 cm above base flow[5] depending on substrate texture (Mahoney & Rood 1998). For seedlings to survive in this zone, stream stage decline must be gradual enough to permit root growth to keep pace. The maximum survivable rate of decline suggested by Mahoney and Rood (1998) is 2.5 cm / day, although more gradual declines would be even more effective. The reader is referred to Mahoney and Rood (1998) for a complete discussion of their 'recruitment box model'.

Given the specific moisture requirements for successful cottonwood seedling establishment, it is not suprising that dendrochronological[6] analyses have shown that natural cottonwood recruitment is associated with 1 in 5, to 1 in 10 year-return flood events (reviewed by Mahoney & Rood 1998). These moderate floods recharge the riparian water table and mobilize sediments to create new seedling nursery sites in the form of meander lobes and lateral bars. Due to the geomorphic changes that they cause, larger scale floods can benefit recruitment for subsequent years or even decades. In early June of 1995, the highest flows on record occurred along many streams in the Oldman River watershed. Following the flood peak, releases from the tributary dams were coordinated to deliver a gradual flow recession of about 2.5 to 5 cm / day. Unprecedented numbers of cottonwood seedlings were observed to survive through 1996 and 1997 at elevations of 1.7 to 3 m above base flow (Rood et al. 1998).

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[5] Base flow is the ground-water component of a stream's flow. It consists of the flow that would remain in the saturated zone below the streambed surface if surface flow was removed (Fetter 1994).

[6] Dendrochronology is the science of dating events and variations in environment in former periods by comparative study of growth rings in trees and aged wood (Webster's 1976).

3. Impacts of Damming & Diversions:

It is not the presence of a dam or diversion, but rather the way it is operated, that has the greatest impact on downstream vegetation. Depending on the objectives of the particular flow management project, water is either diverted for immediate use or stored for future use or gradual release. Common objectives include reducing peak flows to provide flood control or supplementing low flows to provide a reliable supply of water for various uses, particularly irrigation and power generation. In more arid regions, flow during wetter seasons is stored for later use when water supply would naturally be limited. Thus, flow regulation often has the effect of reducing streamflow variability and/or volume.

Although many factors in addition to flow regulation can negatively impact riparian cottonwood forests[7], the regulation of streamflow appears to affect the most basic functioning of the system. Widespread declines in riparian cottonwood forests have been documented along numerous regulated rivers in North America. These declines are usually attributed to one or both of two problems; inadequate seedling replenishment to balance natural attrition in aging populations, and accelerated mortality due to chronic or cumulative water stresses (Table 1). Although both effects are related to modifications in natural streamflow variability and/or volume, they tend to involve different aspects of the natural annual flow pattern (annual hydrograph). For clarity these will be discussed in two general groups, streamflow requirements for seedling recruitment, and those for tree survival and forest maintenance.

As discussed previously, cottonwood seedling recruitment is adapted to capitalize on the barren, moist seedbeds revealed after high springtime streamflows recede. Failed seedling establishment has been consistently linked to reductions or delays of peak-flows and abrupt or sustained low flows during the growing season. High flows drive erosion and deposition along the channel, scouring competing vegetation and laying down new seedbeds. Reduction of peak-flows below certain geomorphic thresholds can cause channel stabilization, meander stagnation that allows encroachment of upland vegetation, all of which result in a shortage of nursery sites for cottonwood seedling establishment. Reduction of springtime peak-flows can also result in a lower, narrower elevational band available for recruitment, leaving seedlings susceptible to burial or removal by subsequent flooding and ice scour.

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[7] Rood & Mahoney 1991b list agricultural clearing, domestic settlement, livestock grazing, direct harvesting, onstream reservoirs, gravel mining, channelization, herbicide spraying and beavers as a few of the prominent factors negatively impacting riparian poplar forests in southern Alberta.

The timing of peak-flow is also critical because mature cottonwoods release their short-lived seeds during only a few weeks in early June. Provided peak flows position newly germinated cottonwood seedlings appropriately, seedling survival depends on subsequent streamflow. The roots of the tiny, drought-sensitive seedlings must maintain contact with the moist, capillary fringe above the floodplain water table. If the rate of water table decline is more rapid than the seedling's root growth, the seedling will loose contact with its water supply and die. Alternately, if streamflow rises enough to inundate the site again, new seedlings are likely to be washed away or buried by sediment.

Streamflow conditions conducive to cottonwood seedling replenishment do not need to occur every year. Consecutive years with high peak-flows can repeatedly remove previously established seedlings. Successful seedling recruitment occurs on average only about once every five to ten years in southern Alberta (reviewed by Mahoney & Rood 1998). Recruitment tends to occur most frequently (1 : 5 years) along meandering reaches with sandy beds (Bradley & Smith 1986, Hughes 1994). Widespread recruitment events, such as the one that occurred in 1995 along the Oldman River (Rood et al. 1998), are rarer, having occurred on average less than once every 30 to 50 years (Stromberg et al. 1993, Hughes 1994, Rood & Mahoney 1991a). Thus, in the time-scale of a cottonwood's lifespan (about 100 years), natural streamflows that support cottonwood recruitment occur relatively infrequently. When streamflow is regulated, these events may occur less frequently, if at all. Reduced frequency of forest replenishment may lead to unbalanced age distributions and eventually to population collapse if left uncorrected.

Cottonwoods remain sensitive to drought stress as they mature. Since their root systems are deeper and more established, mature trees are less likely to become drought stressed than seedlings and saplings, however, they are still dependent on the riparian water table for survival. If the water table drops below their rooting-zone, cottonwoods can become water stressed, and show symptoms such as premature leaf senescence, branch die-back, and complete trunk mortality (Albertson & Weaver 1945, Rood & Mahoney 1991a, Tyree et al. 1994). The effects of repeated drought stress can be cumulative, weakening the trees and leading to increased stress sensitivity.

4. Targeting Flows to Sustain Riparian Forests:

Since each stream has its own combination of environmental constraints and species compositions, flows required to sustain riparian cottonwood forests may vary greatly from reach to reach. Logically, the natural flow regimes that riparian forests have historically been established under and have continued to be maintained by, should be adequate to support those forests' long-term survival. A new equilibrium of vegetation composition may be expected to develop if the pattern of streamflow is altered significantly. For example, consistently lowered flows may produce a new equilibrium state favoring the encroachment of grasslands rather than establishment of pioneer[8] tree species such as cottonwoods. A less extreme change in flow regime may favor cottonwoods closer to their water source, resulting in a narrower band of forest that would tightly parallel the river channel. Although such a regime may feature a reasonably viable riparian forest, a more extensive forest supported by natural conditions would be more diverse and robust, thereby providing more resiliency and greater value for associated wildlife. Thus, the approach taken here will target flows for maintaining and restoring the natural extent and character of riparian cottonwood forests rather than simply trying to ensure the survival of remnant trees.

Cottonwood streamflow requirements can be grouped into four general categories, flows for: 1) tree survival (minimum flows), 2) tree growth (moderate flows), 3) seedbed preparation (peak flows), and 4) seedling and sapling survival (flow ramping and extended moderate flows). It is important to recognize the tolerance thresholds involved in each of these categories for targeting flows to sustain riparian forests as a whole.

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[8] Pioneer forests are capable of establishing in barren areas and initiating the first level of ecological succession (Webster's 1976).

4.1 Minimum flows for forest survival and maintenance:

Many documented instances of riparian cottonwood decline have been associated with reduced minimum flows that have lowered the riparian water table. Water table declines of 1 to greater than 4 m have been documented to cause extensive mortality (approximately 50 to 100%) in adjacent cottonwood groves (Reid 1991, Scott et al. 2000, Scott et al. 1999, Stromberg et al. 1996). These extreme cases define a threshold of unacceptable water table decline. A flow regime for sustaining natural cottonwood groves must avoid crossing this threshold by meeting acceptable minimum flows.

One minimum flow will not suffice for every situation because each reach has unique characteristics that dictate tolerable water table levels for the cottonwoods residing there. For example, different reaches have different channel widths and substrate textures that affect the relative depth of the water table and the extent of the capillary fringe. The moisture requirements of individual trees also vary due to differences in species, age and general health.

Since naturally occurring riparian cottonwoods are adapted to tolerate natural extremes of streamflow, they can survive occasional drought conditions. However, natural minimum flows can be detrimental if the seasonal timing, frequency, and/or duration are altered. For example, cottonwoods are relatively unaffected by low flows during their winter dormancy, but are sensitive to moisture stress during the hottest, driest months of the growing season, typically in July and August. Cottonwoods can survive periods of drought during their growing season, however, the cumulative effects of prolonged or excessively frequent drought conditions may lead to gradual forest deterioration and reduced resiliency to subsequent stresses. Minimum flows should be selected with the goal of maintaining cottonwood survival under chronic implementation. Thus, although isolated instances of more acute stress may be tolerated by cottonwoods, chronic exposure to that same level of stress would be detrimental.

4.2 Moderate flows for tree health and growth:

Minimum flows alone are inadequate to sustain a healthy riparian forest. Moderate flows are required for optimal growth of cottonwoods. Tree growth, which can be measured using radial and branch growth increments[9], is strongly correlated with streamflow (Willms et al. 1998, Stromberg & Patten 1990, 1991, 1996). Thus, as with choosing minimum flows, it is recommended that moderate flows be modeled after trends in naturally occurring streamflows. For example, Stromberg and Patten (1990, 1991, 1996) have suggested that normal growth requires natural average streamflows, with 40 to 60% of natural streamflow being necessary for healthy tree canopies and 74 to 313% of long-term average annual flows being needed for maximum growth. These single streamflow values provide a general guide for selecting moderate flows for cottonwoods.

Cottonwoods are adapted to natural patterns of gradual flow recession following springtime flooding. This natural variability in moderate flows may be important for maintaining the resilience of cottonwood populations. As tends to occur naturally, by exposing trees to a broader range of dynamic river-side conditions, the resiliency of the forest population can be improved to ensure its survival despite the inevitable disturbances and stress associated with high and low flow fluctuations. Thus, instead of implementing a single moderate streamflow, it is recommended that the timing and variability of natural moderate flows be incorporated into the planning of flow regimes by using moving averages, possibly at weekly time-steps, relative to long-term average natural streamflows.

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[9] Radial and branch growth increments are commonly used as indices of tree growth. Radial growth increments are measured from a trunk core or cross-section. The width of each annual tree-ring corresponding to one year of trunk-girth expansion. Similarly, one annual branch growth increment corresponds with the length of shoot elongation resulting after one growing season. Branch increments consist of the internodal distances between bud-scars remaining following each period of winter dormancy.

4.3 Peak flows for channel processes and associated seedling establishment:

Although minimum and moderate flows will favor the survival of mature cottonwood trees, higher flows are also essential to the ongoing viability of riparian forests. Peak flows are important for driving channel dynamics that control erosion and deposition of sediment. As discussed previously, reducing or eliminating peak flows can lead to channel stabilization, meander stagnation and the encroachment of upland vegetation. The resulting shortage of barren, moist nursery sites at appropriate elevations will negatively impact cottonwood seedling production, and so reduce the long-term viability of these riparian forests.

A single, prescribed peak discharge is not suitable for every situation. Since each reach has its own unique combination of bed texture, stream gradient, and vegetation, each will require a slightly different rate of flow to mobilize sediments and create point or lateral bars. Thus, it is useful to refer to natural benchmarks, such as bankfull discharge, that incorporate this variability and relate to important flow thresholds.

Bankfull discharge is recognized as a threshold of flow magnitude conducive to cottonwood seedling replenishment (Auble et al. 1997, Bradley 1982, Howe & Knopf 1991, Johnson 1992). Flows beyond the bankfull threshold may be especially valuable to cottonwoods. A model developed by Richter and Richter (2000) suggests that 125% of bankfull discharge is instrumental in driving channel processes that support the long-term survival of cottonwood forests. Larger floods may enhance recruitment for the next several years (Howe & Knopf 1991, McKay 1996, Scott et al. 1993, 1997). This is probably because larger floods, such as those with greater than 10 year return intervals (Stromberg et al. 1993), cross geomorphic thresholds that cause channel and floodplain instability. Instability in the channel promotes the mobilization of sediments that are subsequently deposited as point and lateral bars and become nursery sites for cottonwood seedling establishment.

The seasonal timing of peak flows is also important for ensuring successful seedling establishment. To maximize seedling recruitment, peak flows should be timed to occur slightly before or during the period of seed dispersal, so that the barren, moistened recruitment zone, positioned 60 to 200 cm above base flow (Mahoney & Rood 1998), is immediately available to be colonized. The window of seed release occurs during early June in southern Alberta, and can extend for several weeks depending on local weather conditions.

4.4 Flow-ramping and extended moderate flows for long-term seedling survival:

The recruitment zone targeted for cottonwood seedling germination can be positioned up to 2 m above the late summer stream stage. In order for the drought sensitive seedlings to survive their first year, the rate of riparian water table decline must not exceed the maximum rate of seedling root growth. The maximum survivable rate of decline suggested by Mahoney and Rood (1998) is 2.5 cm per day. The best way to ensure that this gradual rate of decline is delivered, is to monitor the daily operations of the involved water control structures.

Following their first year, young cottonwood saplings continue to be more sensitive to drought stress than mature trees with more established root systems. Saplings are particularly vulnerable to abrupt reductions in flow since their roots are not yet fully established and root growth may not be able to keep pace with rapid water table declines. Thus, in order to promote long-term survival of cottonwood saplings, variability in the flow regime should not exceed that which would occur naturally. By preserving the natural range of high and low flows that affect the riparian water table, cottonwood root systems will be encouraged to establish at depths that promote healthy tree growth and resiliency to future flow fluctuations.

5. Drafting the 'Poplar Rule Curve':

An important part of developing the necessary streamflow regime for supporting riparian cottonwoods is recognizing the seasonality of the requirements for forest survival and maintenance, tree growth, seedbed preparation, and seedling or sapling survival. Using cottonwoods along the Oldman River at Lethbridge as a general index, Table 2 describes the annual calendar of events related to poplar growth and development (phenology). The cottonwood growing season extends from mid-April until mid-September (shown in grey on Table 2). It is the pattern of flow during this period that is particularly important to the growth and development of riparian cottonwoods, and as such, the growing season defines the Poplar Rule Curve's (PRC) period of concern.

The events that occur during the cottonwood growing season have varied moisture requirements. These requirements are presented in Table 3 for cottonwoods along the Oldman River at Lethbridge. These flow requirements are based on minimum values, and as such are not mutually exclusive. For example, although the streamflow requirements for seedling establishment exceed those for tree maintenance, mature trees will also benefit from the higher flows. These overlaps can be seen when displayed in the context of an annual hydrograph[10] (Figure 2).

It could be impractical and environmentally damaging to generate a standard hydrograph, similar to the one shown in Figure 2, every year. To do so, operators would be required to predict wet versus dry year cycles, and so would face the uncertainty of being able to provide exact flows regardless of upstream supply. Even if it were possible to regulate flow in this manner, the lack of variability in streamflow would probably create artificial channel and forest characteristics, leading to overall reduced resiliency in the system. For example, it would be detrimental to have the same peak recruitment streamflows every year since the previous year's seedlings would be repeatedly removed by high flows the following spring. For these reasons it is appropriate to incorporate a natural degree of variability in the design of flow regimes for sustaining riparian cottonwoods and the channel processes that they depend on.

Where available, the annual record of natural flow can be used to estimate the degree of variability that may be expected to occur naturally. The longer the historic record of flow, the more accurate this estimate will be. Using a weekly interval, flow variability can be described as the probability of occurrence of a particular flow and depicted on an exceedence curve (Figure 3). Each point on the exceedence curve corresponds with the flow observed during the same week of each year during the period on record, in this case

[10] A hydrograph shows the discharge (flow volume) of a stream at a single location as a function of time.

1912 to 1995. Thus, a flow of 225 CMS corresponds with an exceedence of 20%, meaning that in 20% of years, flows of this magnitude or greater have been recorded during this week. The frequency probability of any given point can be calculated by inverting the exceedence value to produce the return interval (RI). Thus, the flow of 225 CMS, that has an exceedence of 20%, equates with a RI of 5. This means that on average, this magnitude of flow has been met or exceeded once every 5 years. Likewise, 100% exceedence flows may be expected to be exceeded every year and 1% exceedence flows may be expected to recur less frequently than once in one hundred years.

If streamflow was regulated each year to meet one of the four general flow requirements for cottonwoods (Figure 2), up to four distinct, artificial 'steps' would be created in each weekly exceedence curve (Figure 4). Although these 'steps' may be based on meeting the basic flow requirements of cottonwoods (where survival flows are met or exceeded every year, flows for growth are provided in 50% of years, and flows for seedling establishment are met in 10% of years), they do not provide the continuum of flow variability that would be present in the natural system.

The goal of the PRC is to integrate the minimum, moderate, and high flow requirements of cottonwoods with a more natural pattern of flow variability. This will produce a more continuous exceedence curve that is somewhat flattened when compared to the exceedence curve for natural streamflow. Instead of depending solely on threshold flow values, the PRC is defined by a composite of three exceedence-based curves (Figure 5) and bankfull discharge. Each of these four components defines a portion of the overall PRC (Figure 6) for any given week of the year according to certain criteria (Table 4).

The first curve included in the PRC, defines the minimum streamflow required for cottonwood survival and maintenance as the 90% exceedence flow. Flows at this level of exceedence are roughly equivalent to the minimum requirement for 40% of natural average weekly flow that is outlined in Table 3. Lower flows will occur naturally, but cottonwoods should be able to tolerate these extreme events as long as the frequency of these events is not increased. Thus, flows with exceedences greater than 90% are not reduced or increased (Figure 5).

Moderate to high PRC flows are defined by the higher of either the 75% of naturalized flow curve, or that flow corresponding with a 50% increase in the RI (eg: a flow that has naturally occurred once every 10 years, now occurs once every 15 years). In general, the 75% curve defines a moderate range of PRC flows and the 50% RI shift defines a higher range of PRC flows. Thus, these two curves (Figure 5) form a gradual bridge that connects the minimum flow requirements for cottonwood survival with those for healthy tree growth and seedling establishment as described in Figure 4.

Finally, the maximum flow required by the PRC is set at 125% of bankfull discharge. This threshold is slightly above bankfull to include flows that may be critical for maintaining the channel dynamics necessary for creating nursery sites for poplar seedling establishment. Figure 6 depicts the combined profile of the three curves and the maximum flow, that have been integrated to form the final PRC curve for a given week along a particular reach.

The calculation of the PRC can be simplified into four PRC 'rules' (Table 4). These 'rules' dictate; 1) there be no reductions to flows with natural exceedences of 90% or greater, 2) flows may not be reduced below the 90% exceedence level, 3) reduction of up to 25% of naturalized flow is acceptable provided that the resulting RI shift is not greater than 50%, and 4) the maximum flow required is 125% of bankfull.

6. Future Directions for Verifying the 'Poplar Rule Curve':

The proposed PRC approach is based on information drawn from a variety of studies on many different stream systems. This background report is intended to provide the general framework within which specific PRC's can be determined for particular river reaches. The next step towards finalizing an operational PRC will be to verify and refine these rules in a more specific context.

Streamflow regulation within the SSRB provides examples of a range of flow modifications that have affected streamside forests to varying degrees. A comparison of these trends will be used to verify and refine PRC flows. Of particular interest are the impacts that different flow regimes have had along the St. Mary, Waterton, and Belly rivers in southern Alberta. Inventories of forest abundance upstream and downstream of major water management structures collected both pre- and post-regulation have been conducted along these rivers by Rood and Heinze-Milne (1989), Reid et al. (1992), and Rood et al. (1995). Their analyses suggest that flow modification along the St. Mary River has contributed to severe declines in downstream cottonwood forests. In comparison, the flow regime imposed on the Waterton River is associated with more moderate declines of downstream cottonwoods, while regulation of the Belly River appears to have had little impact and may even have had a slightly favorable effect on its riparian forests. These three instances provide an excellent opportunity to compare PRC flows with actual test cases.

Given that the proposed PRC will have been optimized for a small number of streams in southern Alberta, it is expected that the details of the PRC rules may need to be revised slightly to address variability present along other reaches and river systems. For example, this variability may relate to channel profiles and sediment characteristics, or species preferences and historic suitabilities of sites for forest establishment. Regardless of these slight refinements, the PRC approach should continue to be based on the streamflow requirements for cottonwood survival and maintenance, growth and development, and seedling establishment and survival, while preserving a more natural range of variability to protect the dynamics and diversity naturally present in these riparian ecosystems.

Literature Cited:

Albertson, F. and J. Weaver. 1945. Injury and death or recovery of trees in prairie climate. Ecological Monographs 15(4):395-433.

Auble, G.T., M.L. Scott, J.M. Friedman, J. Back and V.J. Lee. 1997. Constraints on establishment of plains cottonwood in an urban riparian preserve. Wetlands 17(1):138-148.

Bradley, C.E. 1982. Modified meandering river regimes - effects on plains cottonwood regeneration. M.Sc. Thesis. University of Calgary, Alberta.

Bradley, C. and D.G. Smith. 1986. Plains cottonwood recruitment and survival on a prairie meandering river floodplain, Milk River, southern Alberta and northern Montana. Canadian Journal of Botany 64:1433-1442.

Cordes, L.D., F.M.R. Hughes and M. Getty. 1997. Factors affecting the regeneration and distribution of riparian woodlands along a northern prairie river: the Red Deer River, Alberta, Canada. Journal of Biogeography 24:675-695.

Fenner, P., W.W. Brady and D.R. Patton. 1985. Effects of regulated water flows on regeneration of Fremont cottonwood. Journal of Range Management 38(2):135-138.

Fetter, C.W. 1994. Applied hydrogeology. 3rd Edition. Prentice-Hall Inc., Upper Saddle River, NJ. 691pp.

Howe, W.H. and F.L. Knopf. 1991. On the imminent decline of Rio Grande cottonwoods in central New Mexico. The Southwestern Naturalist 36(2):218-224.

Hughes, F.M.R. 1994. Environmental change, disturbance and regeneration in semi-arid floodplain forests. In: Environmental change in drylands: biogeographical and geomorphological perspectives. John Wiley & Sons Ltd. pp. 321-345.

Johnson, W.C. 1992. Dams and riparian forests: case study from the upper Missouri River. Rivers 3(4):229-242.

Johnson, W.C. 1998. Adjustment of riparian vegetation to river regulation in the Great Plains, USA. Wetlands 18(4):608-618.

Johnson, W.C., R.L. Burgess and W.R. Keammerer. 1976. Forest overstory vegetation and environment on the Missouri River floodplain in North Dakota. Ecological Monographs 46(1): 59-84.

Mahoney, J.M. and S.B. Rood. 1993. The potential effects of an operating plan for the Oldman River Dam on riparian cottonwood forests. Oldman River Dam Mitigation Program Downstream Vegetation Project Report, Volume II. Prepared for Alberta Public Works, Supply and Services. 108+pp.

Mahoney, J.M. and S.B. Rood 1998. Streamflow requirements for cottonwood seedling recruitment: an integrative model. Wetlands 8(4):634-645.

McKay, S.J. 1996. The impact of river regulation on establishment processes of riparian black cottonwood. M.Sc. Thesis, University of Washington, Seattle, WA.

Miller, J.R., T.T. Schulz, N.T. Hobbs, K.R. Wilson, D.L. Schrupp and W.L Baker. 1995. Changes in the landscape structure of a southeastern Wyoming riparian zone following shifts in stream dynamics. Biological Conservation 72:371-379.

Reid, D.E. 1991. Cottonwood mortality assessment at Police Point Park, Alberta. In: Proceedings of the Biology and Management of Southern Alberta's Cottonwoods Conference, May 3-4. Edited by: S.B. Rood and J.M. Mahoney. University of Lethbridge, Alberta.

Reid, D.E., L. Zilm, J.M. Mahoney and S.B. Rood. 1992. Riparian vegetation of the St. Mary, Belly and Waterton River valleys, Alberta. Report #CE01190 by: Hardy BBT Limited and the University of Lethbridge, Alberta.

Richter, B.D. and H.E. Richter. 2000. Prescribing flood regimes to sustain riparian ecosystems along meandering rivers. Conservation Biology 14(5):1467-1478.

Rood, S.B. and C. Bradley. 1993. Assessment of riparian cottonwoods along the Bow River downstream from Calgary, Alberta. Report prepared for: Trout Unlimited Canada.

Rood, S.B. and Heinze-Milne. 1989. Abrupt downstream forest decline following river damming in southern Alberta. Canadian Journal of Botany 67:1744-1749.

Rood, S.B. and J.M. Mahoney. 1991a. The biology of riparian cottonwood forests in the Oldman River Basin - Oldman River Dam Mitigation Program Downstream Vegetation Project Report - Volume I. Prepared for: Alberta Public Works, Supply and Services.

Rood, S.B. and J.M. Mahoney. 1991b. The importance and extent of cottonwood forest decline downstream from dams. Pages 1-9 in: S.B. Rood & J.M. Mahoney (eds.), The biology and management of southern Alberta's cottonwoods. University of Lethbridge, Alberta.

Rood, S.B. and J.M. Mahoney. 1995. River damming and riparian cottonwoods along the Marias River, Montana. Rivers 5(3):195-207.

Rood, S.B., J.M. Mahoney, D.E. Reid and L. Zilm. 1995. Instream flows and the decline of riparian cottonwoods along the St. Mary River, Alberta. Canadian Journal of Botany 73:1250-1260.

Rood, S.B. and J.M. Mahoney. 2000. Revised instream flow regulation enables cottonwood recruitment along the St. Mary River, Alberta, Canada. Rivers 7(2):109-125.

Rood, S.B., K. Taboulchanas, C.E. Bradley and A.R. Kalischuk. 1999. Influence of flow regulation on channel dynamics and riparian cottonwoods along the Bow River, Alberta. Rivers 7(1):33-48.

Rood S.B, A.R. Kalischuk and J.M. Mahoney. 1998. Initial cottonwood seedling recruitment following the flood of the century of the Oldman River, Alberta, Canada. Wetlands 8(4):557-570.

Rood, S.B., J.M. Mahoney, D.E. Reid and L. Zilm. 1995. Instream flows and the decline of riparian cottonwoods along the St. Mary River, Alberta. Canadian Journal of Botany 73:1250-1260.

Scott, M.L., G.T. Auble and J.M. Friedman. 1997. Flood dependency of cottonwood establishment along the Missouri River, Montana, USA. Ecological Applications 7(2):677-690.

Scott, M.L., G.T. Auble, J.M. Friedman, L.S. Ischinger, E.D. Eggleston, M.A. Wondzell, P.B. Shafroth, J.T. Back and M.S. Jordan. 1993. Flow recommendations for maintaining riparian vegetation along the Upper Missouri River, Montana. National Biological Survey, National Ecology Research Center, Fort Collins, CO. 36pp.

Scott M.L., G.C. Lines and G.T. Auble. 2000. Channel incision and patterns of cottonwood stress and mortality along the Mojave River, California. Journal of Arid Environments 44:399-414

Scott, M.L., P.B. Shafroth and G.T. Auble. 1999. Responses of riparian cottonwoods to alluvial water table declines. Environmental Management 23(3):347-358.

Snyder, W.D. and G.C. Miller. 1991. Changes in plains cottonwoods along the Arkansas and South Platte Rivers - eastern Colorado. Prairie Naturalist 23(3):165-176.

Snyder, W.D. and G.C. Miller. 1992. Changes in riparian vegetation along the Colorado River and Rio Grande, Colorado. Great Basin Naturalist 52: 357-363.

Stromberg, J.C. and D.T. Patten. 1990. Riparian vegetation instream flow requirements: a case study from a diverted stream in the eastern Sierra Nevada, California, USA. Environmental Management 14(2):185-194.

Stromberg, J.C. and D.T. Patten. 1991. Instream flow requirements for cottonwoods at Bishop Creek, Inyo County, California. Rivers 2(1):1-11.

Stromberg, J.C. and D.T. Patten. 1996. Instream flow and cottonwood growth in the eastern Sierra Nevada of California, USA. Regulated Rivers: Research & Management 12:1-12.

Stromberg, J.C., B.D. Richter, D.T. Patten and L.G. Wolden. 1993. Response of a sonoran riparian forest to a 10-year return flood. Great Basin Naturalist 53(2):118-130.

Stromberg, J.C. and R. Tiller. 1996. Effects of groundwater decline on riparian vegetation of semiarid regions: The San Pedro, Arizona. Ecological Applications 6(1):113-131.

Tyree, M.T., K.J. Kolb, S.B. Rood and S. Patino. 1994. Vulnerability to drought-induced cavitation of riparian cottonwoods in Alberta: a possible factor in the decline of an ecosystem? Tree Physiology 14:455-466.

Webster's New Collegiate Dictionary. 1976. Thomas Allen & Son Ltd., Toronto, ON.

Willms, J., S.B. Rood, W. Willms and M. Tyree. 1998. Branch growth of riparian cottonwoods: a hydrologically sensitive dendrochronological tool. Trees 12:215-223.

Table 1. Documented examples of riparian cottonwood declines associated with flow regulation along streams in North America.

Authors:	River and region	Inadequate replenishment	Forest stress or mortality
Auble et al. 1997	Boulder Cr., CO	X	X
Bradley & Smith 1986, Bradley 1982	Milk R., AB & MO	X	X
Cordes et al. 1997	Red Deer R., AB	X	
Fenner et al. 1985	Salt R., AZ	X	X
Howe & Knopf 1991	Rio Grande, NM	X	
Johnson 1998, Johnson 1992, Johnson et al. 1976	Missouri R., ND	X	X
Johnson 1998	Platte R., NB	X	X
McKay 1996	Nisqually R., WA	X	
McKay 1996	Cowlitz R., WA	X	
Miller et al. 1995	North Platte R., WY	X	X
Rood et al. 1998 & 1999, Rood & Bradley 1993	Bow R., AB	X	
Rood & Mahoney 2000, Rood et al. 1995,	St. Mary R., AB	X	X
Reid et al. 1992, Rood & Heinze-Milne 1989	Waterton R., AB	X	X
Rood & Mahoney 1995	Marias R., MO	X	
Snyder & Miller 1992	Colorado R., CO	X	X
Snyder & Miller 1991	Arkansas R., CO	X	X
Stromberg & Tiller 1996	San Pedro R., AZ	X	X

Table 2. Weekly calendar of riparian cottonwood phenology along the Oldman River at Lethbridge, AB. (the growing season is shaded)

Week	1st day of week	Growth & Development	Seedlings (< 1 year old)	Saplings (> 1 year old)
1-5	Jan.	dormant		dormant
6-9	Feb.	dormant		dormant
10-13	Mar.	dormant		dormant
14	Apr.2	dormant		dormant
15	Apr.9	dormant		dormant
16	Apr.16	flowering		dormant
17	Apr.23	flowering		bud flush shoot & root growth
18	Apr.30	bud flush flowering		bud flush shoot & root growth
19	May.7	bud flush flowering		bud flush shoot & root growth
20	May.14	shoot growth flowering		bud flush shoot & root growth
21	May.21	shoot growth		shoot & root growth
22	May.28	shoot growth seed release	germination root growth	shoot & root growth
23	Jun.4	shoot growth seed release	germination root growth	shoot & root growth
24	Jun.11	shoot growth seed release	germination root growth	shoot & root growth
25	Jun.18	shoot growth seed release	germination root growth	shoot & root growth
26	Jun.25	shoot growth	germination root growth	shoot & root growth
27	Jul.2	shoot growth	germination root growth	shoot & root growth
28	Jul.9	shoot growth	root growth	shoot & root growth
29	Jul.16	shoot growth	root growth	shoot & root growth
30	Jul.23	shoot growth	root growth	shoot & root growth
31	Jul.30	bud set / leaf maintenance	root growth	shoot & root growth
32	Aug.6	bud set / leaf maintenance	root growth	bud set shoot & root growth
33	Aug.13	bud set / leaf maintenance	root growth	bud set shoot & root growth
34	Aug.20	bud set / leaf maintenance	root growth	bud set / leaf maintenance
35	Aug.27	bud set / leaf maintenance	root growth	bud set / leaf maintenance
36	Sep.3	senescence	root growth	leaf maintenance
37	Sep.10	senescence	root growth	leaf maintenance
38	Sep.17	senescence	bud set root growth	senescence
39	Sep.24	senescence / abscission	bud set root growth	senescence
40	Oct.1	abscission	bud set root growth	senescence / abscission
41	Oct.8	abscission	bud set root growth	abscission
42	Oct.15	dormant	dormant	dormant
43	Oct.22	dormant	dormant	dormant
44	Oct.29	dormant	dormant	dormant
45-48	Nov.	dormant	dormant	dormant
49-52	Dec.	dormant	dormant	dormant

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10-13	Mar.	dormant		dormant
14	Apr.2	dormant		dormant
15	Apr.9	dormant		dormant
16	Apr.16	flowering		dormant
17	Apr.23	flowering		bud flush shoot & root growth
18	Apr.30	bud flush flowering		bud flush shoot & root growth
19	May.7	bud flush flowering		bud flush shoot & root growth
20	May.14	shoot growth flowering		bud flush shoot & root growth
21	May.21	shoot growth		shoot & root growth
22	May.28	shoot growth seed release	germination root growth	shoot & root growth
23	Jun.4	shoot growth seed release	germination root growth	shoot & root growth
24	Jun.11	shoot growth seed release	germination root growth	shoot & root growth
25	Jun.18	shoot growth seed release	germination root growth	shoot & root growth
26	Jun.25	shoot growth	germination root growth	shoot & root growth
27	Jul.2	shoot growth	germination root growth	shoot & root growth
28	Jul.9	shoot growth	root growth	shoot & root growth
29	Jul.16	shoot growth	root growth	shoot & root growth
30	Jul.23	shoot growth	root growth	shoot & root growth
31	Jul.30	bud set / leaf maintenance	root growth	shoot & root growth
32	Aug.6	bud set / leaf maintenance	root growth	bud set shoot & root growth
33	Aug.13	bud set / leaf maintenance	root growth	bud set shoot & root growth
34	Aug.20	bud set / leaf maintenance	root growth	bud set / leaf maintenance
35	Aug.27	bud set / leaf maintenance	root growth	bud set / leaf maintenance
36	Sep.3	senescence	root growth	leaf maintenance
37	Sep.10	senescence	root growth	leaf maintenance
38	Sep.17	senescence	bud set root growth	senescence
39	Sep.24	senescence / abscission	bud set root growth	senescence
40	Oct.1	abscission	bud set root growth	senescence / abscission
41	Oct.8	abscission	bud set root growth	abscission
42	Oct.15	dormant	dormant	dormant
43	Oct.22	dormant	dormant	dormant
44	Oct.29	dormant	dormant	dormant
45-48	Nov.	dormant	dormant	dormant
49-52	Dec.	dormant	dormant	dormant

Table 3. Weekly flow requirements of riparian cottonwoods along the Oldman River at Lethbridge, AB. (the growing season is shaded)

		Mature Trees:		Saplings (> 1 year old)		Seedlings (< 1 year old)	
Week	Date	Survival & Maintenance	Growth & Reproduction	Survival	Growth	Fringe Establishment (1 : 5-10 yr)	General Establishment (1 : 30-50 yr)
1-5	Jan.	nat ave min		nat ave min		nat ave min	
6-9	Feb.	nat ave min		nat ave min		nat ave min	
10-13	Mar.	nat ave min		nat ave min		nat ave min	
14	Apr.2	nat ave min		nat ave min		nat ave min	
15	Apr.9	nat ave min		nat ave min		nat ave min	
16	Apr.16	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	nat wk ave	
17	Apr.23	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	nat wk ave	
18	Apr.30	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	nat wk ave	
19	May.7	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	nat wk ave	
20	May.14	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	nat wk ave	
21	May.21	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	nat wk ave	
22	May.28	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	1:10yr peak	1:30yr peak
23	Jun.4	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	1:10yr peak	1:30yr peak
24	Jun.11	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	1:10yr peak	1:30yr peak
25	Jun.18	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
26	Jun.25	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
27	Jul.2	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
28	Jul.9	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
29	Jul.16	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
30	Jul.23	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
31	Jul.30	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
32	Aug.6	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
33	Aug.13	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
34	Aug.20	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
35	Aug.27	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
36	Sep.3	nat ave min		60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
37	Sep.10	nat ave min		60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
38	Sep.17	nat ave min		nat ave min		nat ave min	
39	Sep.24	nat ave min		nat ave min		nat ave min	
40	Oct.1	nat ave min		nat ave min		nat ave min	
41	Oct.8	nat ave min		nat ave min		nat ave min	
42	Oct.15	nat ave min		nat ave min		nat ave min	
43	Oct.22	nat ave min		nat ave min		nat ave min	
44	Oct.29	nat ave min		nat ave min		nat ave min	
45-48	Nov.	nat ave min		nat ave min		nat ave min	
49-52	Dec.	nat ave min		nat ave min		nat ave min	

Table 4. Criteria for calculating PRC flows during a given week of the year.

Criteria:		PRC Flow:
1. If exc. of natural flow	>/= 90%	**natural flow**
	< 90%	*(refer to criterion 2)*
2. If 75% of natural flow	</= natural 90% exc. flow	**natural 90% exc. flow**
	> natural 90% exc. flow	*(refer to criterion 3)*
3. If reduction to 75% of natural flow causes a RI increase of	</= 50% of the natural RI	**75% natural flow**
	> 50% of the natural RI	*(refer to criterion 4)*
4. If 75% of natural flow	< 125% Bankfull	**flow corresponding to 50% increase of natural RI**
	>/= 125% Bankfull	**125% bankfull**

Figure 1. Cross-section of a streambank showing the extent of moistened substrates and the suitability of zones for cottonwood seedling establishment (adapted from Mahoney & Rood 1998).

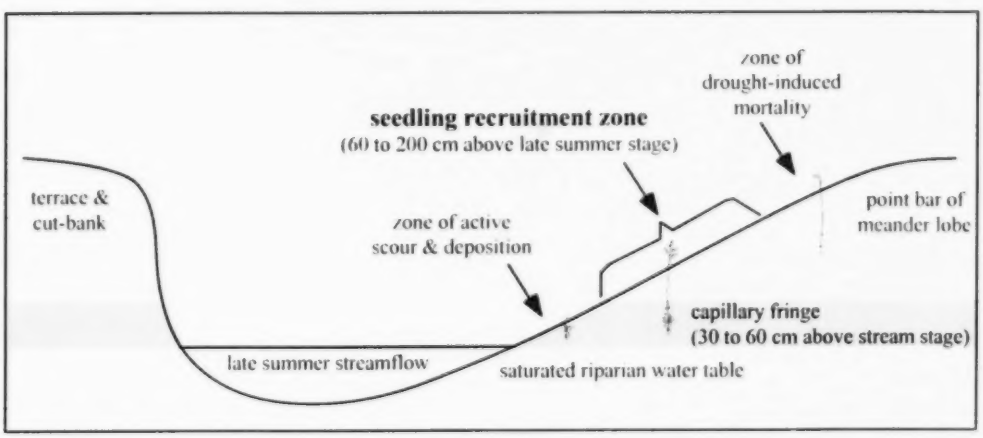

Table 3. Weekly flow requirements of riparian cottonwoods along the Oldman River at Lethbridge, AB. (the growing season is shaded)

Week	Date	Mature Trees:		Saplings (> 1 year old)		Seedlings (< 1 year old)	
		Survival & Maintenance	Growth & Reproduction	Survival	Growth	Fringe Establishment (1 : 5-10 yr)	General Establishment (1 : 30-50 yr)
1-5	Jan.	nat ave min		nat ave min		nat ave min	
6-9	Feb.	nat ave min		nat ave min		nat ave min	
10-13	Mar.	nat ave min		nat ave min		nat ave min	
14	Apr.2	nat ave min		nat ave min		nat ave min	
15	Apr.9	nat ave min		nat ave min		nat ave min	
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17	Apr.23	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	nat wk ave	
18	Apr.30	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	nat wk ave	
19	May.7	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	nat wk ave	
20	May.14	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	nat wk ave	
21	May.21	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	nat wk ave	
22	May.28	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	1:10yr peak	1:30yr peak
23	Jun.4	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	1:10yr peak	1:30yr peak
24	Jun.11	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	1:10yr peak	1:30yr peak
25	Jun.18	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
26	Jun.25	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
27	Jul.2	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
28	Jul.9	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
29	Jul.16	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
30	Jul.23	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
31	Jul.30	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
32	Aug.6	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
33	Aug.13	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
34	Aug.20	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
35	Aug.27	40% nat wk ave	nat wk ave	60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
36	Sep.3	nat ave min		60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
37	Sep.10	nat ave min		60% nat wk ave	nat wk ave	- 2.5 cm/day to nat wk ave	
38	Sep.17	nat ave min		nat ave min		nat ave min	
39	Sep.24	nat ave min		nat ave min		nat ave min	
40	Oct.1	nat ave min		nat ave min		nat ave min	
41	Oct.8	nat ave min		nat ave min		nat ave min	
42	Oct.15	nat ave min		nat ave min		nat ave min	
43	Oct.22	nat ave min		nat ave min		nat ave min	
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2. If 75% of natural flow	</= natural 90% exc. flow	**natural 90% exc. flow**
	> natural 90% exc. flow	*(refer to criterion 3)*
3. If reduction to 75% of natural flow causes a RI increase of	</= 50% of the natural RI	**75% natural flow**
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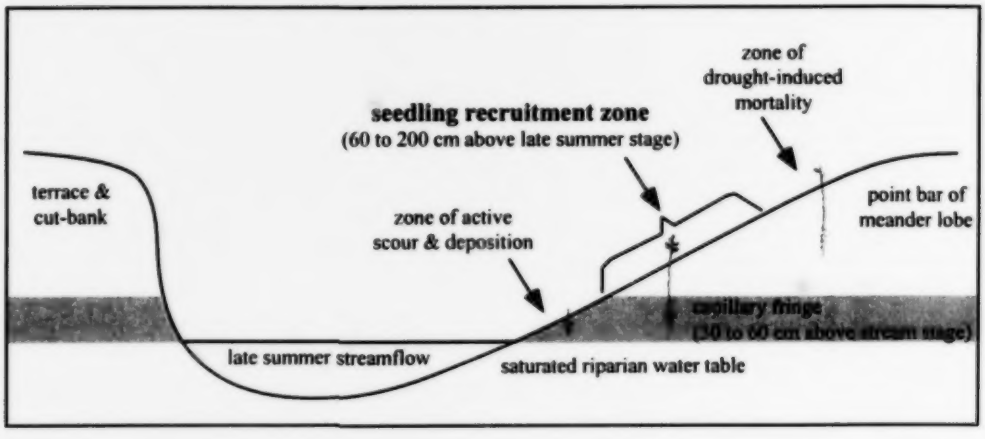

Figure 2. Generalized flows required by cottonwoods along the Oldman River near Fort Macleod. Flows required for growth and development consist of natural weekly average flows. Flows for survival and maintenance are 50% of the natural weekly average. Flows for fringe seedling establishment consist of a 1:10 year peak flow during the period of seed release followed by a 2.5 cm / day stage decline. Flows for general seedling establishment include a 1:30 year peak flow followed by a 2.5 cm / day stage decline. The natural ranges of weekly minimum and maximum flows (from 1912 to 1995) are indicated as dotted lines without symbols.

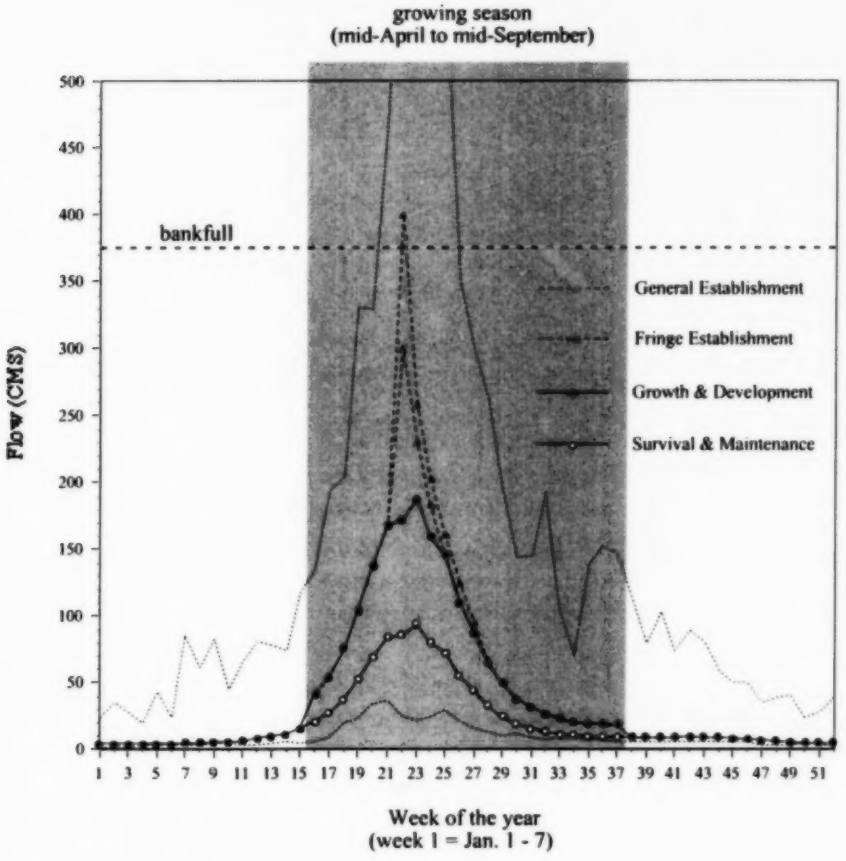

Figure 3. Exceedence curve for naturalized streamflows along the Oldman River near Fort Macleod during week 22 (May 28 - June 3), 1912-1995.

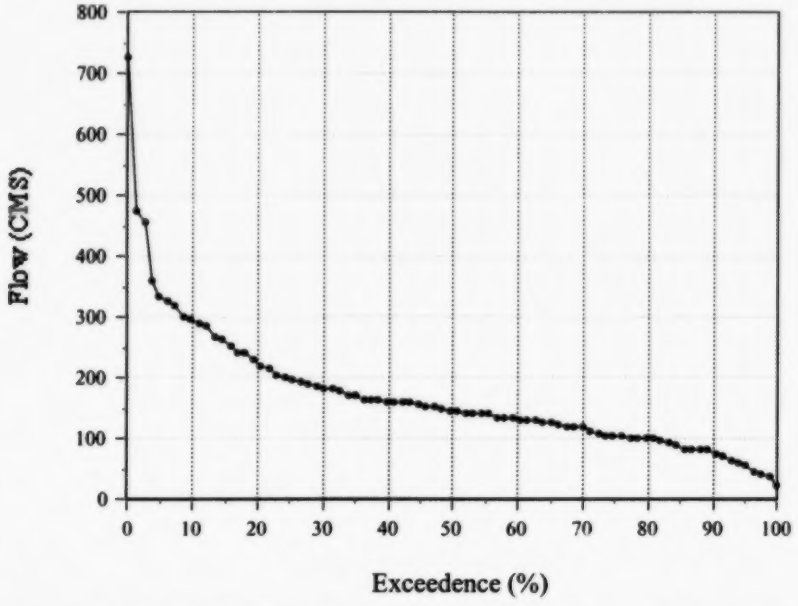

Figure 4. Threshold-based streamflow requirements for cottonwoods in relation to the exceedence curve for naturalized streamflow along the Oldman River near Fort Macleod during week 22 (May 28 - June 3), 1912-1995.

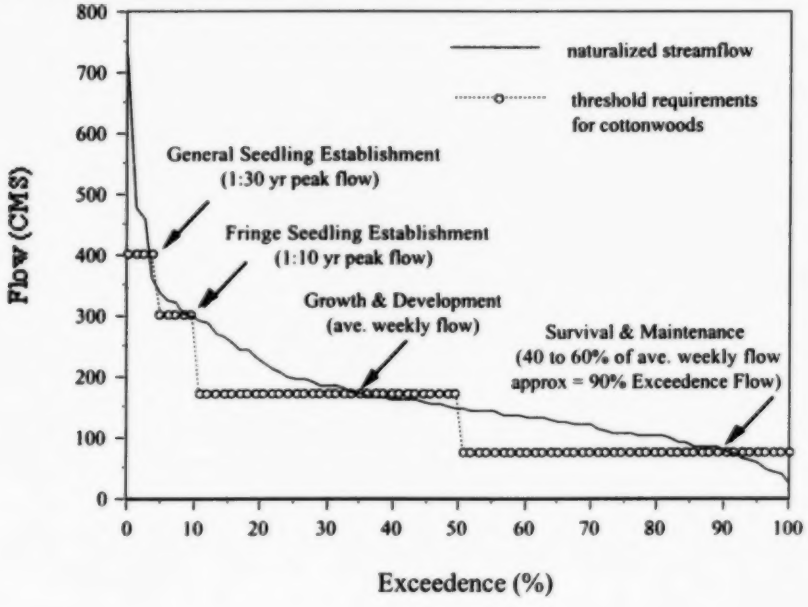

Figure 5. Three exceedence-based curves that each satisfy a portion of the streamflow requirements of cottonwoods along the Oldman River near Fort Macleod during week 22 (May 28 - June 3), 1912-1995.

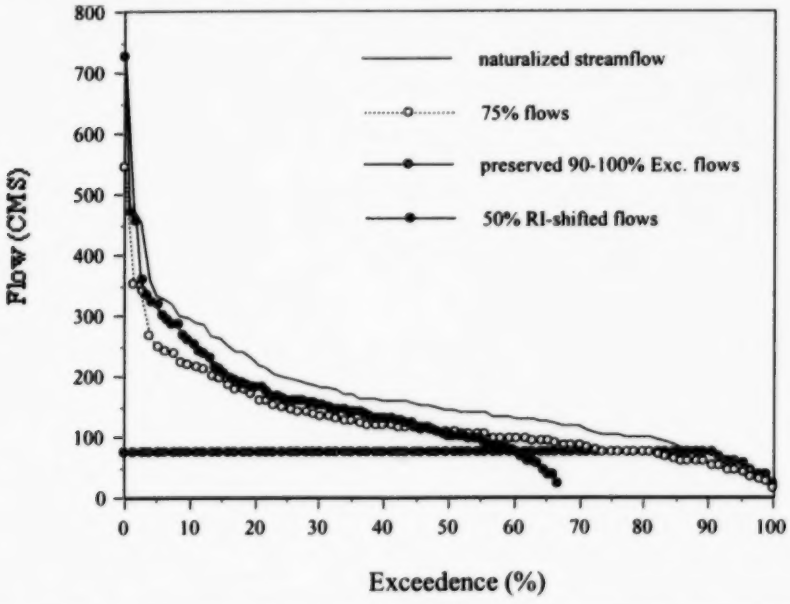

Figure 6. PRC for cottonwoods in relation to the exceedence curve for naturalized streamflow along the Oldman River near Fort Macleod during week 22 (May 28 - June 3), 1912-1995.